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RESEARCH MEMORANDUM

VARIATION OF THE PRESSURE LIMITS OF FLAME PROPAGATION WITH TUBE DIAMETER FOR PROPANE-AIR MIXTURES

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SUMMARY

The change in the pressure limits of flame propagation with tube diameter was accurately measured for two purposes: (a) to establish the relation of the critical tube diameter for propagation with the total pressure and the composition of the propane-air mixtures; (b) to relate this measured critical diameter for propagation with other combustion properties, especially quenching distance, flame velocity, and minimum ignition energies.

Low-pressure propagation limits were measured for quiescent propane-air mixtures in cylindrical glass tubes with inside diameters of 66, 47, 38, 22, and 16 millimeters. Mixtures containing 2.3 to 9.5 percent by volume propane in air were studied. The concentration range from the lean limit for propagation to the stoichiometric mixture gave the most regular and reproducible results; therefore, only that limited concentration range was used for the quantitative evaluation of the relation between critical diameter and pressure.

The critical diameter for flame propagation was found to be proportional to the pressure raised to the -0.97 power for a stoichiometric mixture. The pressure effect was smaller for leaner mixtures. The critical tube diameters were on the average 1.43 times as large as quenching distances measured by the minimum width of a rectangular slit for flash-back of a Bunsen flame. The reported effect of pressure on the minimum slit width is comparable to the effect of pressure on the critical diameter as measured in this work. It was concluded from these facts that the critical tube diameter for propagation of a flame in a quiescent mixture is a quenching distance.

Critical diameter was also found to be related to two other combustion properties. A correlation was found between flame speed and the reciprocal of the critical diameter; in addition, a correlation was found between critical diameter and the square root of the minimum ignition energy.

INTRODUCTION

Knowledge of which fuel-air mixtures will burn under certain conditions and what determines their combustibility is desirable in the design of a satisfactory jet-engine combustor. So many processes occur simultaneously in the combustor that it is very difficult to gain an understanding of any single process from a study of combustor performance. The problem of determining the conditions that limit the combustion of a fuel-air mixture and the mechanism of the limiting processes can best be studied under controlled conditions in the laboratory. First it is important to know the factors limiting combustion in a homogeneous fuel-air mixture. It has long been known (reference 1) that there are concentration limits for the process of combustion; that is, the mixture may contain too much or too little fuel to burn. Many researchers have investigated the concentration limits at atmospheric pressure (reference 2); a few have determined the effect of reduced pressure on these limits (references 3 to 6). It has been observed that the geometry of the apparatus can affect the limits of flame propagation: Sir Humphrey Davy recognized as early as 1816 that limiting diameters exist for flame propagation and used the effect as the basis for a miners' safety lamp. Recently, a limited systematic study of the effects of reduced pressure and fuel concentration on critical diameters determined by measurement of low-pressure inflammability limits has been reported (reference 7).

Part of the fundamental combustion program being conducted at the NACA Lewis laboratory includes systematic studies of various combustion properties of hydrocarbon-air mixtures. Investigations are being made of rates of flame propagation (references 8 and 9), concentration limits of propagation, pressure limits of propagation (references 6 and 10), ignition energies, and quenching distances. One purpose of the programs is to determine the interrelation between these properties and to understand the mechanisms of the processes.

It has been suggested (references 6, 10, and 11) that low-pressure limits of inflammability may be governed by quenching effects. The work presented herein was undertaken to obtain suitable data with which to investigate this possibility and for later use in gaining a better understanding of the process by which flame propagation is limited by tube diameter. In addition, it was desired to learn more about the relation of the critical diameter for flame propagation to other combustion properties, particularly rate of flame propagation and minimum ignition energy.

Previous preliminary work at this laboratory (reference 10) reported the variation of the pressure limits of flame propagation with tube diameter for some propane-air mixtures. The critical diameters for propagation of propane-air flames are presented herein for a range of fuel concentrations. The effect of pressure on critical diameter is also evaluated. The relations between critical diameter for propagation and quenching distance for flash-back, minimum ignition energy at low pressure, and rate of flame propagation are discussed.

EXPERIMENTAL

Apparatus. - The apparatus for determination of the limits of propagation is sketched in figure 1. It consisted of a flame tube with a large-diameter ignition section, a fuel mixing and metering system, a spark ignition system, and an evacuation system.

The glass flame tubes combined an ignition section and a propagation section smoothly sealed together to form a one-piece unit. The propagation sections were 4 feet long and had inside diameters of 66, 47, 38, 28, 22, and 16 millimeters. Each 4-foot tube was sealed to an ignition section 90 millimeters in diameter and 10 inches long, with a 65/40 spherical ground glass inner joint sealed to the lower end of the section. The ground joints of the ignition sections mated with an outer joint on the stem of a 35-millimeter-bore stopcock, which provided a connection between the flame tubes and a 47-liter carboy.

The ignition system consisted of a pair of spark electrodes entering the ignition section from the stem of the stopcock below and a power supply capable of delivering a rapid capacitance spark.

The entire pressure-limit apparatus was made of glass in order to eliminate leaks and to prevent absorption of propane by rubber connections. The evacuation system for the setup consisted of a mercury diffusion pump backed by a mechanical pump. A cold trap was provided to freeze water vapor out of the evacuated gases. With this arrangement it was possible to pump the entire system down to 1 micron of mercury.

The apparatus incorporated features of the setup used for the preliminary work (reference 10) as well as additional refinements. The large-diameter ignition section was used, as in the preliminary work, to avoid the effects of tube diameter on the ignition of the mixtures and to provide sufficient volume for dissipation of any excess ignition energy. The plenum chamber served to absorb the pressure rise due to combustion in the flame tube, and thus, to minimize pressure disturbances on the flame front. These disturbances, particularly as the flame passed from the large ignition section through the constriction into the narrower flame tube, were the chief cause of irreproducible and uncertain results in the preliminary investigation.

A capacitance spark was chosen as the ignition source in order to eliminate the convection currents arising from heated coils, prolonged passing of an induction spark, and so forth since it was believed that these currents would tend to disturb the flame as it passed into the propagation section of the flame tube.

Preparation of propane-air mixtures. - Propane-air mixtures were prepared and stored in a 47-liter carboy (see fig. 1). The carboy was evacuated to 0.3 millimeter of mercury or less, as read on the McLeod gage, and propane of 99-mole-percent minimum purity was admitted until its pressure corresponded to the desired percentage of atmospheric pressure (assuming ideal gas behavior). The propane pressure was read with a cathetometer on the precision absolute manometer. Air passed slowly through Ascarite (to remove carbon dioxide) and through Anhydrone and a 4-foot column of anhydrous alumina (to remove water) was then admitted to bring the carboy to atmospheric pressure. The propane and air were mixed by means of motor-driven vanes sealed into the carboy through a metal bellows.

After the pressure limit of such a mixture was determined, leaner mixtures were made from it by subsequent dilutions with air. These dilutions were measured on the precision manometer. This procedure gave satisfactory results, as shown by the fact that the pressure limits of corresponding original mixtures and those made by dilution were the same within the experimental error of the limit determinations.

The effectiveness of carbon dioxide and water removal from the air was not checked; however, treated and untreated air gave the same results within experimental error.

Procedure. - For each run, the flame tube and all the system up to the mixture-storage carboy were evacuated to a pressure of less than 0.1 millimeter. The pumping system was then closed off, and the fuel-air mixture was admitted to the flame tube to the desired test pressure. Next, the pressure in the plenum chamber was equalized to the mixture pressure by adding or pumping out room air. The large stopcock between flame tube and plenum chamber was slowly opened, and the mixture was ignited.

The pressure limit for each propane-air mixture was fixed by repeated trials at various pressures, until a pressure was found such that the flame was extinquished at the mouth of the narrow tube. The limits were, in general, very precise since an increase of 2 millimeters pressure would allow the flame to propagate the entire length of the narrow tube. Thus, the experiments themselves made it clear that the mouth of the narrow tube was acting as a critical diameter. For the apparatus used, the critical diameter was therefore defined as the minimum diameter of a circular opening through which a flame would propagate in a mixture of a given composition at a given pressure.

For very lean mixtures, close to the lean composition-inflammability limit, flames were occasionally observed that extinquished somewhere between the mouth and the upper end of the narrow tube. For the sake of consistency, however, the pressure-limit in these cases was taken as the pressure at which extinction occurred in the mouth of the tube.

Most of the pressure limits were established to within ± 1 millimeter of mercury. That is, two pressures were found that differed by 2 millimeters, the higher of which permitted flame propagation throughout the narrow tube, whereas the lower caused extinction at its mouth. The limit recorded was the average of the two pressures. Erratic flame behavior was encountered over certain concentration ranges, but even in these cases the reproducibility was good.

RESULTS AND DISCUSSION

Curves of pressure limit against volume percent propane in air for tubes of 66, 47, 38, 28, 22, and 16 millimeters inside diameter are presented in figure 2. In general, the minimum pressure for propagation is higher the smaller the tube; at a given pressure, the composition range of inflammability narrows as the tubes become smaller. The curves vary in a regular manner except over a composition range of about 4.5 to 6.5 percent propane, where many crossovers and lobes are present. In this composition-pressure region, the flames were visually observed to be quite fast and were oscillatory and often irregular. Thus, it is believed that the apparently anomalous behavior is due to aerodynamic effects on the flame as it approaches the mouth of the narrow tube.

From the preliminary work done at this laboratory (reference 10), it was tentatively concluded that, for a given concentration, the tube diameter was inversely proportional to the pressure of the limit of propagation. The present investigation, in which refined technique was used, shows that the tube diameter is inversely proportional to the pressure raised to a power slightly less than 1. In figure 3, the logarithm of the critical diameter is plotted against the logarithm of the pressure limit for four concentrations: 2.50, 3.00, 3.50, and 4.03 (stoichiometric) percent propane in air. The slopes of the lines in all cases show a smaller dependence than the -1 power of the pressure and the pressure dependence decreases with decreasing propane concentration. The range of exponents of pressure is -0.97 to -0.76. The slopes reported are calculated slopes of the best straight lines through the data as determined by the method of least squares.

The data presented give the pressure-composition boundary for flame passage through a tube, with tube diameter as a parameter. The same type of information is obtained by quenching-distance measurements. Therefore, if the pressure-limits for propagation through tubes are affected by quenching, the present data should be comparable to quenching-distance data. Friedman and Johnston (reference 11) have measured propane-air quenching distances by determining the narrowest slit through which a Bunsen flame will flash back when mixture flow is reduced; propane concentration was varied and pressure was the parameter. Log-log plots of pressure against minimum slit width for the data of these investigators are given in figure 4 for propane concentrations of 3.00, 3.50, and 4.03 (stoichiometric) percent by volume. The slopes of the lines obtained also were calculated by the method of least squares, and agree well with the slopes calculated for the present data. In addition, the slopes of the two sets of lines (figs. 3 and 4) vary in the same manner with propane concentration.

The pressure dependencies of critical diameter and minimum slit width are compared in the following table:

Propane in air (volume percent)	Negative power of pressure-critical diameter	Negative power of pressure-minimum slit width
4.03	0.97	0.88
3.50	.92	.85
3.00	.85	.83

The magnitudes of the critical tube diameter for flame propagation and the minimum slit width for flash-back of a Bunsen flame differ. If critical diameter is governed by quenching, as is minimum slit width for flash-back, then the two measurements should be related by a constant factor which depends on the geometry of the apparatus. The ratios of the two distances are given in table I. The minimum slit widths were read from the extrapolated data of reference 11, figure 4.

Inspection of the data in table I shows that the ratio may vary slightly with propane concentration; however, the over-all average is 1.43, with a maximum value of 1.68 and a minimum value of 1.24. This average of 1.43 is very similar to the value of 1.35 for the ratio of tube diameter for flash-back to slit width for flash-back given in reference 11.

From the similarity in the pressure effect on critical diameter and on minimum slit width, and from the fact that the two measurements are related by a constant which is very similar to the constant determined for flash-back alone, it may be concluded that critical diameter is a quenching distance.

The measurement of critical diameters provides another means of determining quenching distance. The technique should be quite useful under certain conditions, particularly at low pressures where large pumping apparatus is required to maintain a flow system.

As a fundamental property of combustion, quenching distance would be expected to be related to other fundamental properties. Three correlations are presented, two with the rate of flame propagation and one with minimum ignition energy.

In figure 5, the flame speeds of three propane-air mixtures at atmospheric pressure are plotted against the reciprocals of the critical diameters for the same mixtures. The flame speeds are from the data of reference 12; the critical diameters are from the extrapolated lines of figure 3. The range of compositions covered is 3.0 to 4.03 percent by volume. Figure 6 shows a similar correlation between flame speeds and quenching distances measured at various elevated temperatures. The flame speeds of reference 13 for 3.50- and 4.03-percent propane mixtures at 27°, 127°, 210°, and 285° C are plotted against the reciprocals of the minimum slit widths for the same temperatures (reference 11).

It would be desirable to relate critical diameter to flame speed at reduced pressures. However, in view of the controversy surrounding low-pressure flame speed measurements, no correlation was attempted with the flame-speed data available at present.

A correlation between critical diameter and minimum ignition energy is presented in figure 7. The square roots of the minimum ignition energies at various pressures are plotted against the critical diameters at the same pressures, for propane concentrations of 3.0 and 4.0 percent. The ignition energies were obtained from the data of Blanc, Guest, Von Elbe, and Lewis (reference 14). The critical diameters are from the extrapolated 3.0- and 4.03-percent lines of figure 3. The same correlation has previously been reported between ignition energies and quenching distances obtained from the ignition experiments (reference 15).

The correlations presented point out interrelations among the following three fundamental combustion properties: quenching distance, flame velocity, and minimum ignition energy. A comprehensive theory of combustion should be capable of predicting these relations.

SUMMARY OF RESULTS

From the investigation of the variation of the pressure-limits of propagation with tube diameter for propane-air flames, the following results were obtained:

(1) The critical diameter for flame propagation was found to be proportional to the -0.97 power of the mixture pressure for stoichiometric mixtures. The pressure dependence decreased with decreasing concentration of propane in air.

(2) The critical diameters measured were an average of 1.43 times as large as quenching distances measured by flash-back through a rectangular slit.

(3) The critical diameter was found to be related inversely to the flame speed and directly to the square root of the minimum ignition energy.

CONCLUSIONS

The following conclusions were reached as a result of the investigation:

(1) Critical diameter determined from the low-pressure limits of inflammability is a quenching distance.

(2) Interrelations exist between the fundamental combustion properties of quenching distance and the minimum ignition energy measured at reduced pressures, and between quenching distance and flame speed at various concentrations and temperatures.

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TABLE I - RATIO OF CRITICAL DIAMETER TO MINIMUM SLIT WIDTH

Propane in air, (volume percent)	Mixture pressure, (atm)	Critical diameter, d_2 (cm)	Minimum slit width, d_1 (cm)	d_2/d_1
4.03	0.0300	6.6	4.18	1.58
	.0473	4.7	2.80	1.68
	.0555	3.8	2.44	1.56
	.0684	2.8	2.03	1.38
	.0882	2.2	1.64	1.34
	.1397	1.6	1.10	1.46
				Average, 1.50
3.50	0.0338	6.6	4.30	1.54
	.0513	4.7	3.00	1.57
	.0611	3.8	2.60	1.46
	.0793	2.8	2.08	1.35
	.1052	2.2	1.65	1.33
	.1658	1.6	1.12	1.43
				Average, 1.45
3.00	0.0417	6.6	4.78	1.38
	.0632	4.7	3.40	1.38
	.0789	3.8	2.83	1.34
	.1052	2.8	2.25	1.24
	.1422	2.2	1.75	1.26
	.2305	1.6	1.18	1.35
				Average, 1.33
				Over-all average, 1.43

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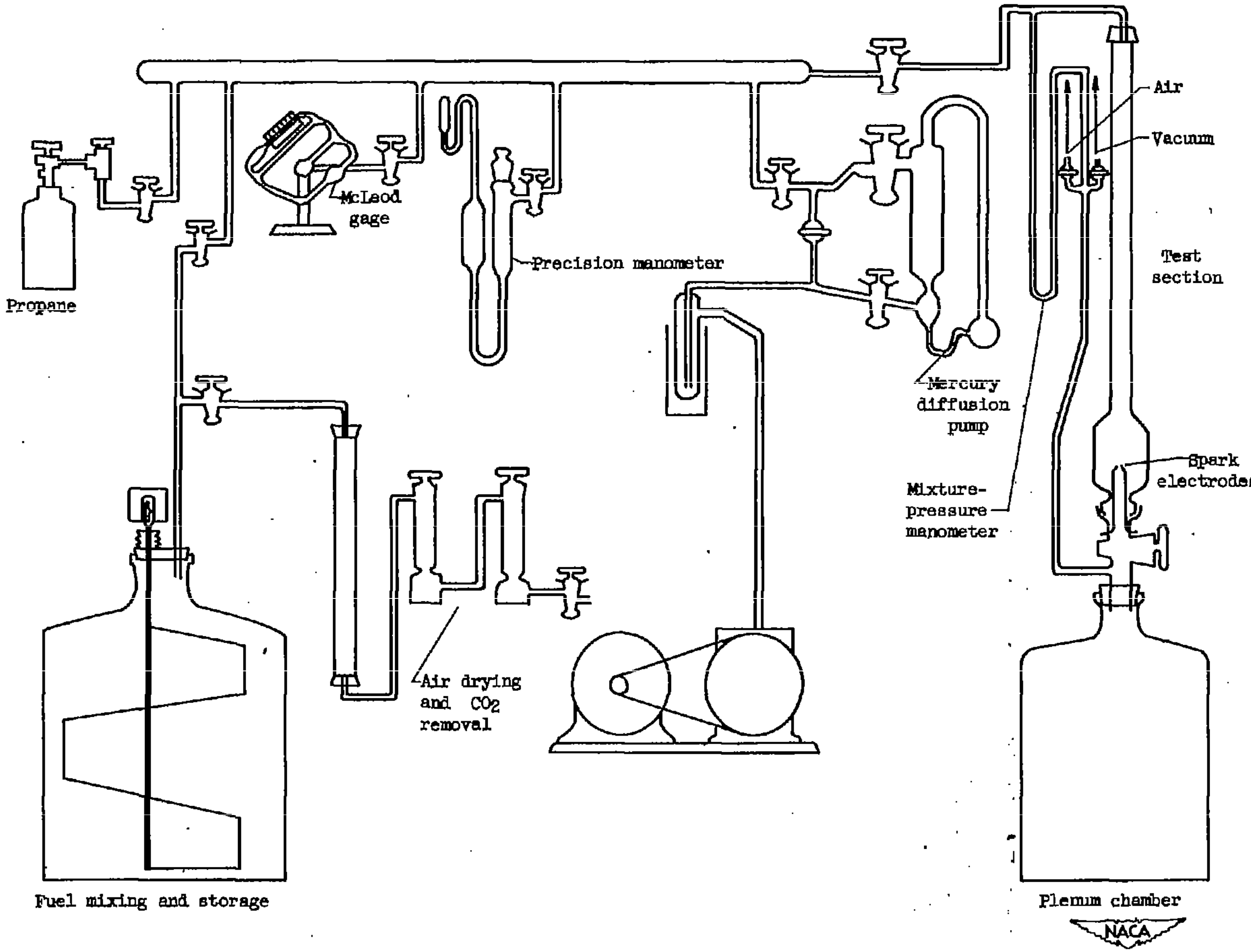

Figure 1. - Pressure limit apparatus.

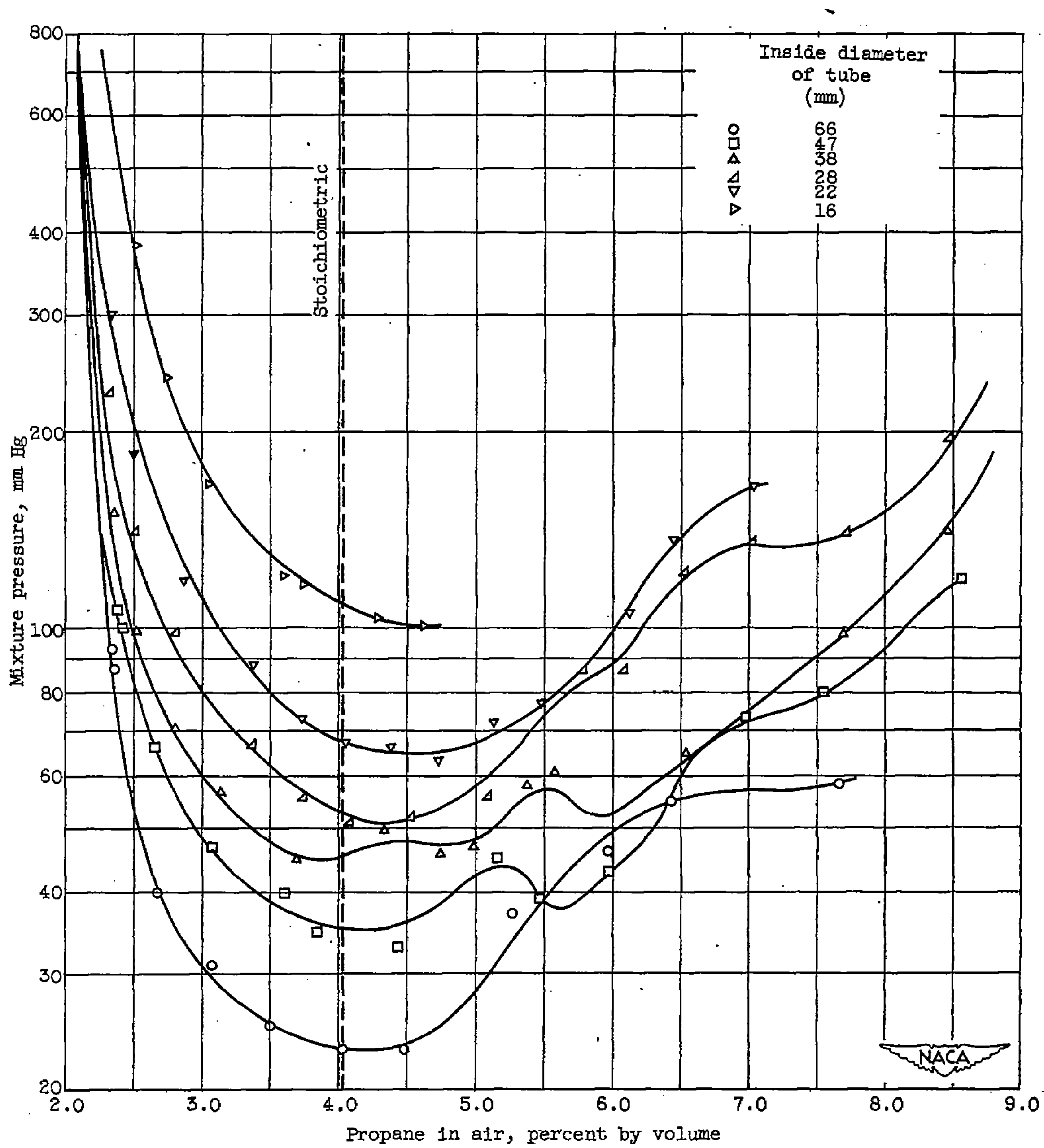

Figure 2. - Effect of tube diameter on pressure-inflammability limit.

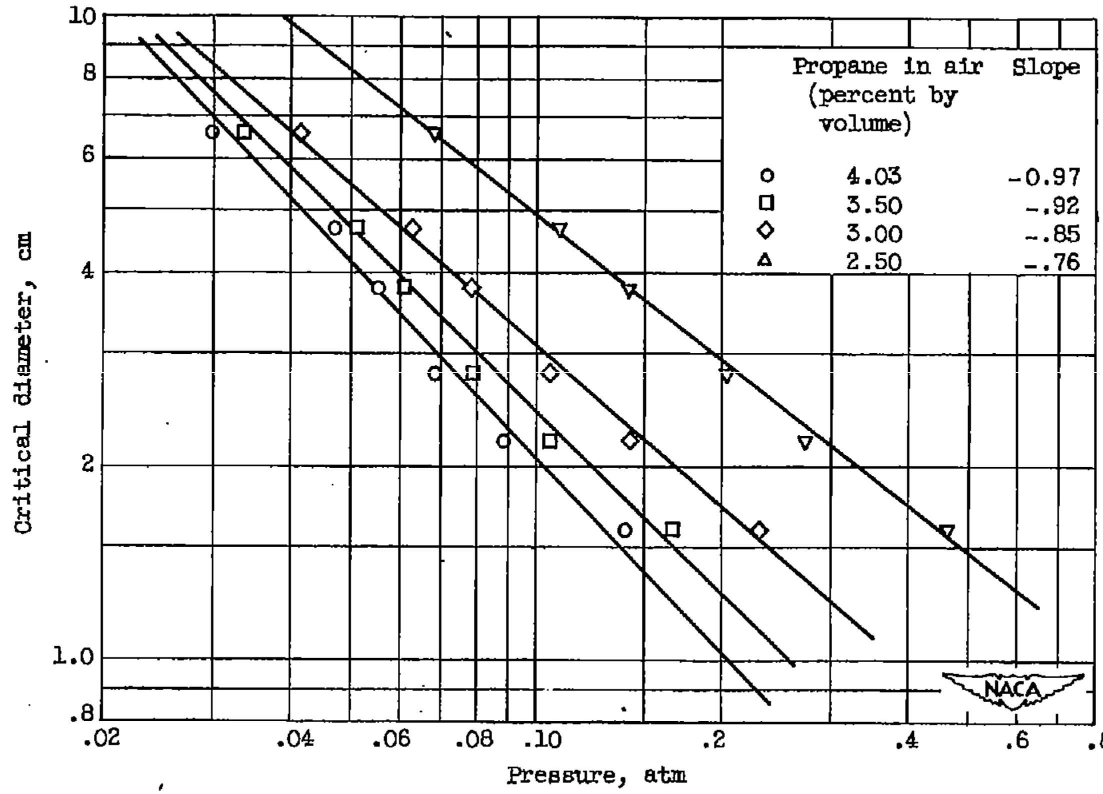

Figure 3. - Relation of critical diameter to pressure.

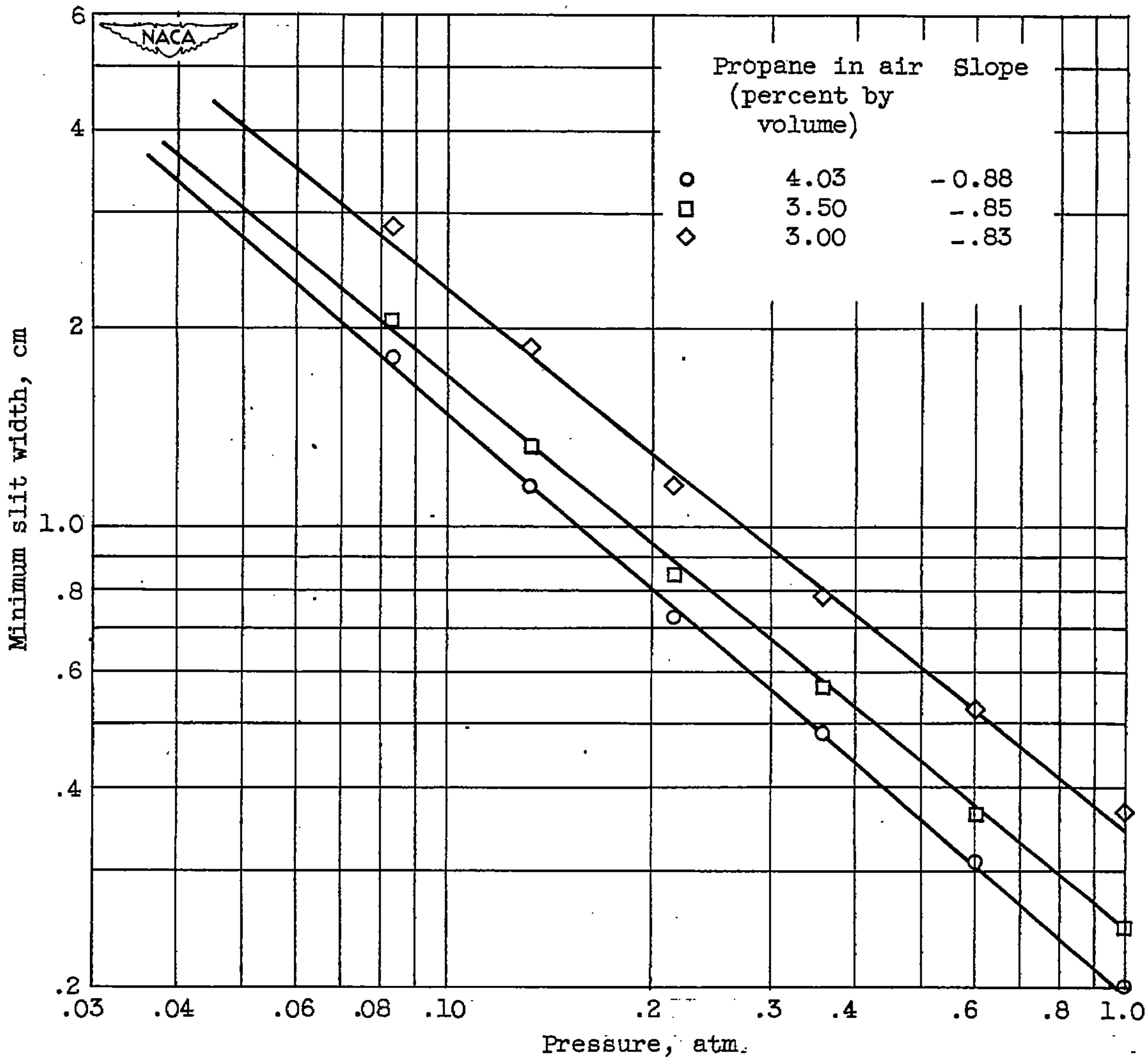

Figure 4. - Relation of minimum slit width to pressure. (Data from reference 11.)

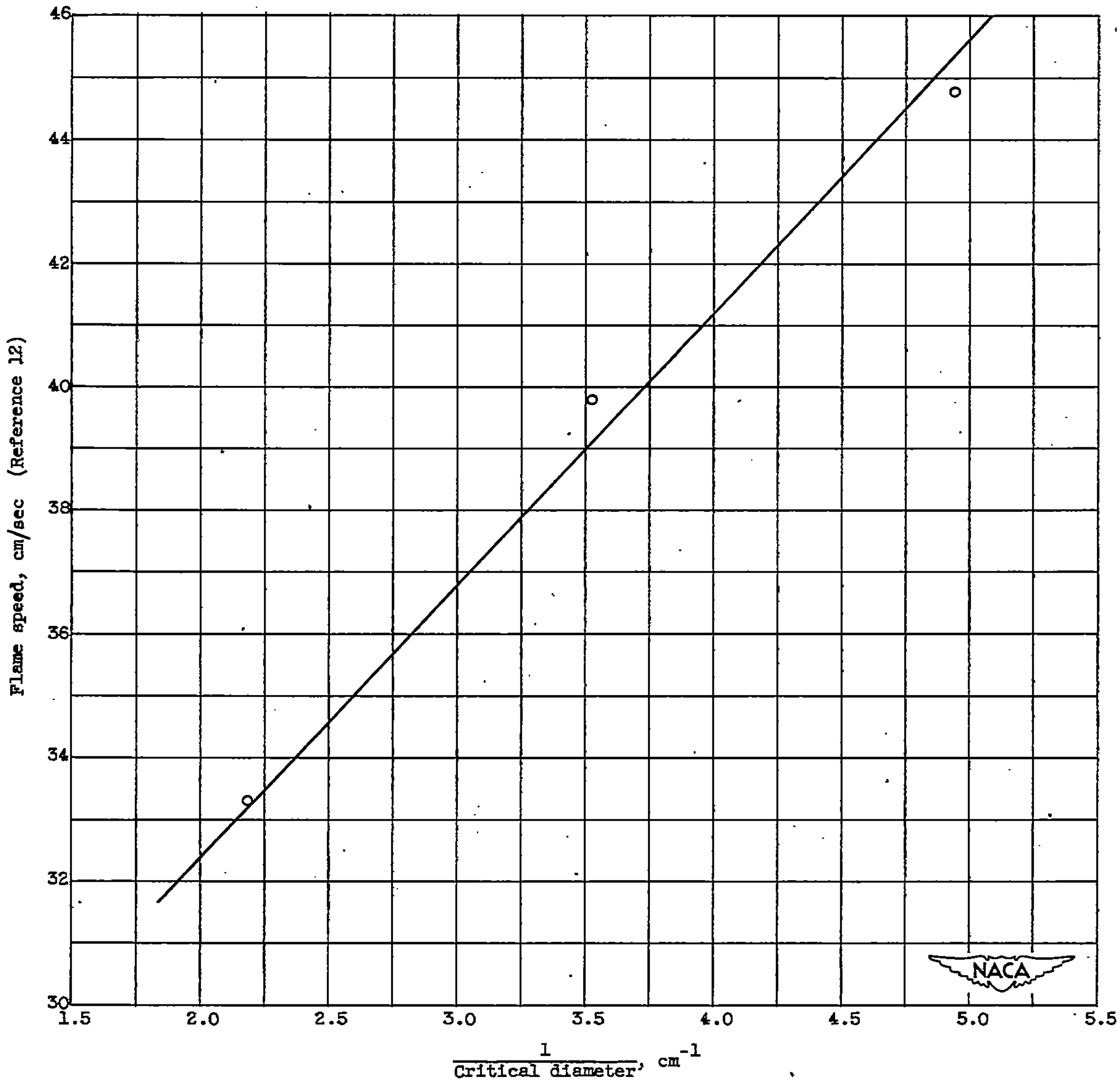

Figure 5. - Correlation of flame speed with critical diameter for various propane-air mixtures at atmospheric pressure.

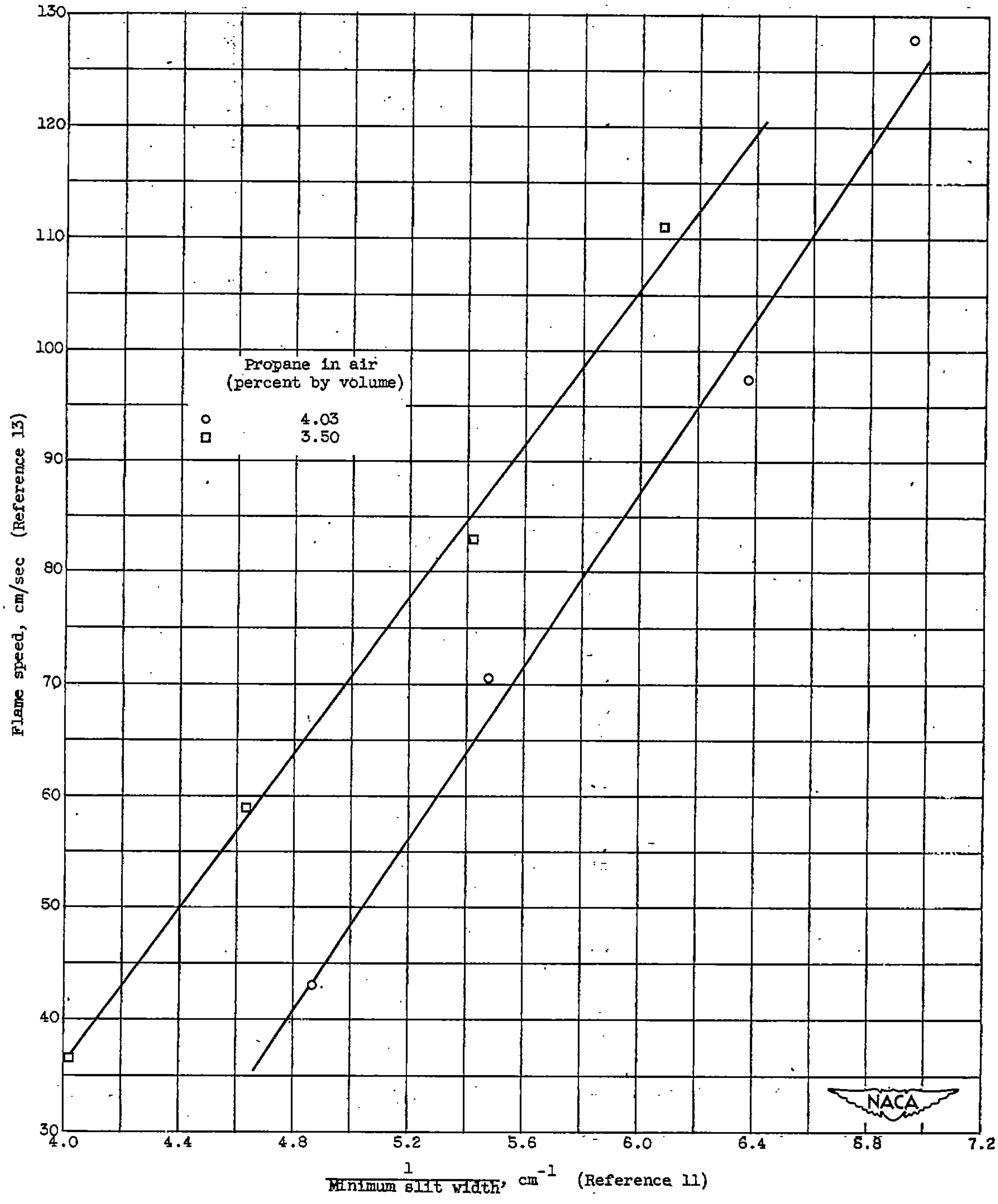

Figure 6. - Correlation of flame speed with minimum slit width at various temperatures for propane-air mixtures.

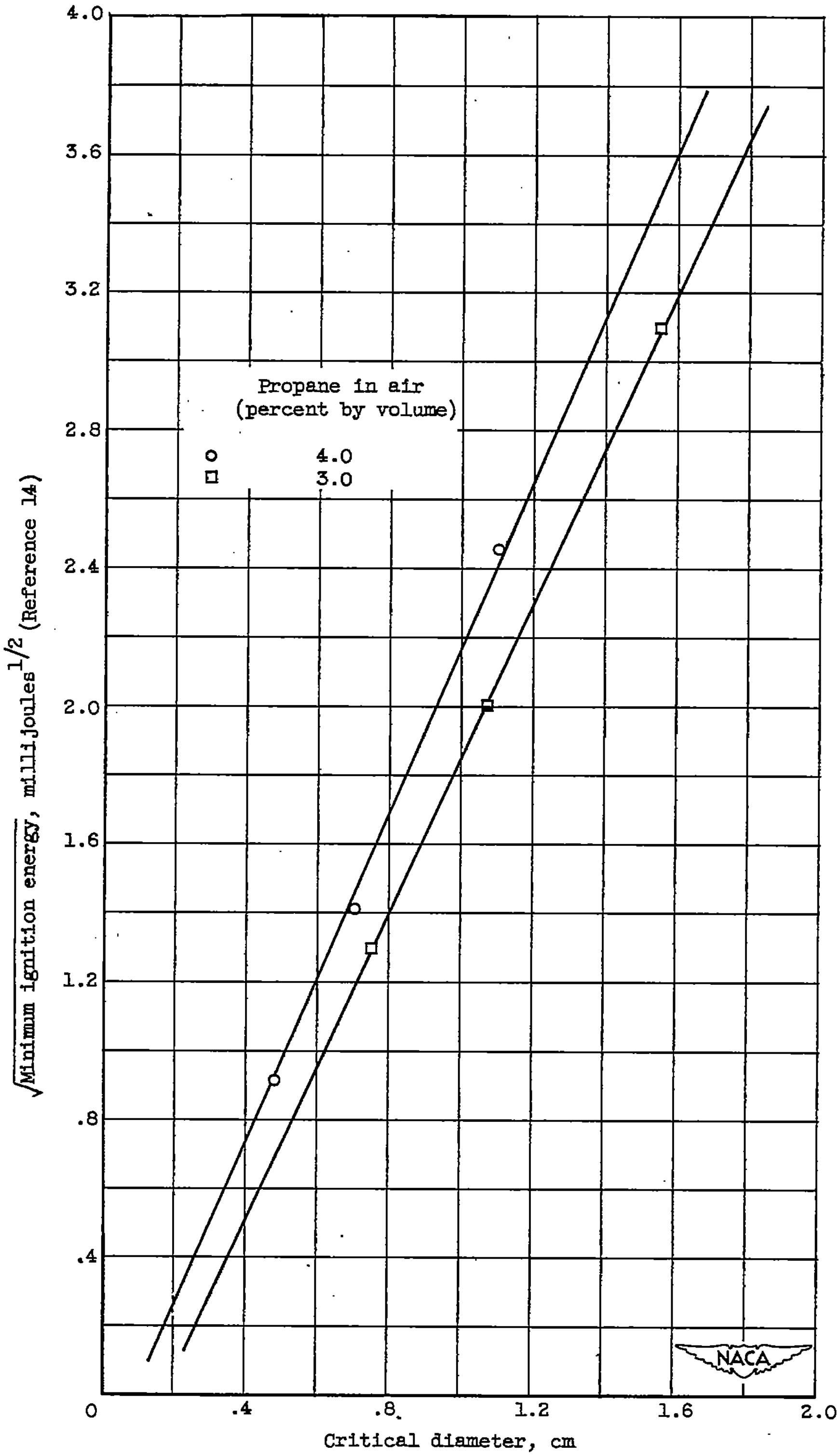

Figure 7. - Correlation of minimum ignition energy with critical diameter at various pressures.